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MODELING OF SOIL WATER TO INSURE A SUITABLE DEPTH AND SPACING OF SUBSURFACE DRIP IRRIGATION TUBING FOR ALFALFA

Rocio Guadalupe Reyes Esteves[1*]; Donald Carl Slack [2]

[1]University of Arizona - Department of Agricultural and Biosystems Engineering. 1177 E. 4th Street, Shantz Building, Room 609. Tucson, AZ, USA 85721.

rocior@email.arizona.edu - +1 (520) 658-7217 (*Autor de correspondencia)

[2]University of Arizona - Department of Agricultural and Biosystems Engineering. 1177 E. 4th Street, Shantz Building, Room 627. Tucson, AZ, USA 85721

Abstract

A major design issue in the implementation of a subsurface drip irrigation system is the determination of the appropriate depth of placement of the drip emitters to allow basic farming operations with heavy equipment while still providing adequate water to the crop. In this study, the program HYDRUS-2D is used to determine the wetting pattern from a subsurface drip emitter installed at 50 cm for three soils typically found in Southern CA, a Sandy Clay Loam (SCL), a Clay Loam (CL) and a Loam (L). The model was used to determine the extent of wetting above, and laterally from the drip tubing after twelve hours of irrigation the day of the cut with an irrigation frequency of every three days. The vertical “rise” of water above the drip line after this irrigation period was 27 cm, 30 cm and 22 cm for the SCL, CL, and L, respectively. Then classical soil mechanics theory was utilized to calculate the increase in stress on soil at any depth due to a load on the surface from a typical farm tractor. The minimum depth placement to avoid failure would be 40 cm below the surface in a SCL soil. A similar analysis for the CL and L yielded minimum installation depths of 35 cm and 40 cm respectively. This type of analysis is helpful in determining the depth of placement of subsurface drip irrigation lines to ensure adequate trafficability of soil irrigated with subsurface drip irrigation systems.

Keywords: soil moisture, HYDRUS 2-D, soil shear strength.

Introduction

The use of precision irrigation systems and their adequate design, management, and scheduling plays an important role for the water application in the right place, with the right amount, at the right time. These practices are still under research and require a lot of experimental work, studies, and analysis to determine their viability and applicability (Al-Karadsheh *et al.*, 2002). When irrigation engineers design an irrigation system, they try to maximize irrigation efficiency which is defined as the ratio of the volume of water that is taken up by the crop to the amount of irrigation water applied (American Society of Civil Engineers [ASCE], 1978). Subsurface Drip Irrigation (SDI) systems have the potential to increase that efficiencysince water can be applied inshort durations andvarious amounts to meet the crop water requirements.

Initial applications of SDI systems were to row crops such as corn or cotton where drip tubes were placed 8 -10 cm below the surface of alternate rows. This allowed farm equipment such as tractors with cultivators and fertilizer or pesticide applicators to traverse the rows which did not have drip tubes under them in a “controlled traffic” system. As the technology continued to evolve, farmers became interested in utilizing SDI on “extensively” grown crops which are not planted in rows but are sown continuously throughout the field (Slack *et al.*, 2010). One such extensively grown crop in the US is the forage crop alfalfa which has rooting depths of up to 2 meters. This crop has been increasing steadily in thirteen western states of the U.S. More than 400 000 hectares have been added during the last decade (National Agricultural Statistics Service, USDA).

Alfalfais harvested as frequently as every two weeks, and the harvest operation requires a tractor and other heavy equipment to be driven over much of the surface of the field. Thus, drip tubing cannot be placed so close to the soil surface that the surface becomes wetted, or the tractor would be at best leave deep damage in the field or at worst to become “stuck.” A practical alternative has been to place the drip tubing at a depth high enough that the soil surface will not become wetted but is still shallow enough to deliver water to the plant roots. Up to this point in time, appropriate depths for such systems have been determined by “trial and error” for each new soil and equipment condition (Slack *et al.*, 2010).

The general objective of this study was todeterminea suitable depth forplacement of subsurface drip irrigation tubing using well-established modeling techniques and classical soil mechanics theory. The specific objectives were to determine the vertical extent of the wetted zone above subsurface drip irrigation tubes in three different soils, Sandy Clay Loam (SCL), Clay Loam (CL) and Loam (L). An additional objective was to determine the increased stress at specific depths due to the weight of a farm tractor on the soil surface and, to use this information together with soil strength properties to determine the appropriate depth of placement of drip tubes. Finally the ultimate objective is to ensure that soil failure does not occur when the tractor is driven over the drip tubing while irrigation is in progress. Another result of the modeling exercise was the determination of the lateral extent of the wetted zone which can be used to determine the appropriate lateral spacing between drip line tubing.

Materials and methods

In this study, the program HYDRUS-2D is used to determine the wetting pattern from a subsurface drip emitter for three soil types typically found in Southern CA with an irrigation time of twelve hours and a frequency of every three days. Then classical soil mechanics theory was applied to calculate the increase in stress on soil at any depth due to a load on the surface from a typical farm tractor used in harvest operations.

This information was then used in conjunction with soil strength properties such as shear strength as a function of soil moisture content to determine the minimum permissible depth of placement of drip line tubing to ensure that soil failure does not occur. The lateral extent of the wetting pattern at the end of irrigation was used to determine the maximum spacing at which an SDI system will provide adequate crop irrigation throughout the field in a particular soil. Table 1 shows the soil properties of the three soils utilized in this study.

Table 1. Soil properties for SCL, CL, and L soils.

Soil type	Sandy Clay Loam (SCL)	Clay Loam (CL)	Loam (L)
Sand (%)	60.0	30.0	40.0
Silt (%)	15.0	35.0	40.0
Clay (%)	25.0	35.0	20.0
Bulk density (gm/cc)	1.62	1.56	1.51
Saturated MC (%)	43.0	48.0	46.0
50% AWC	5.00	7.00	7.00
FC (90% sat)	27.0	36.0	28.0
Saturated conductivity (cm/hr.)	1.13	0.43	1.55
Angle internal friction (degrees)	32.5	25.0	30.0
Cohesion (kg/cm^2) Compacted	0.63	0.84	0.76
Cohesion (kg/cm^2) Saturated	0.15	0.15	0.15
Cohesion (kg/cm^2) 90% Sat.	0.13	0.13	0.13

Based on this data, a relationship between cohesion and soil moisture was made. Figure 1 is a graphical representation of these relationships for the three soils.

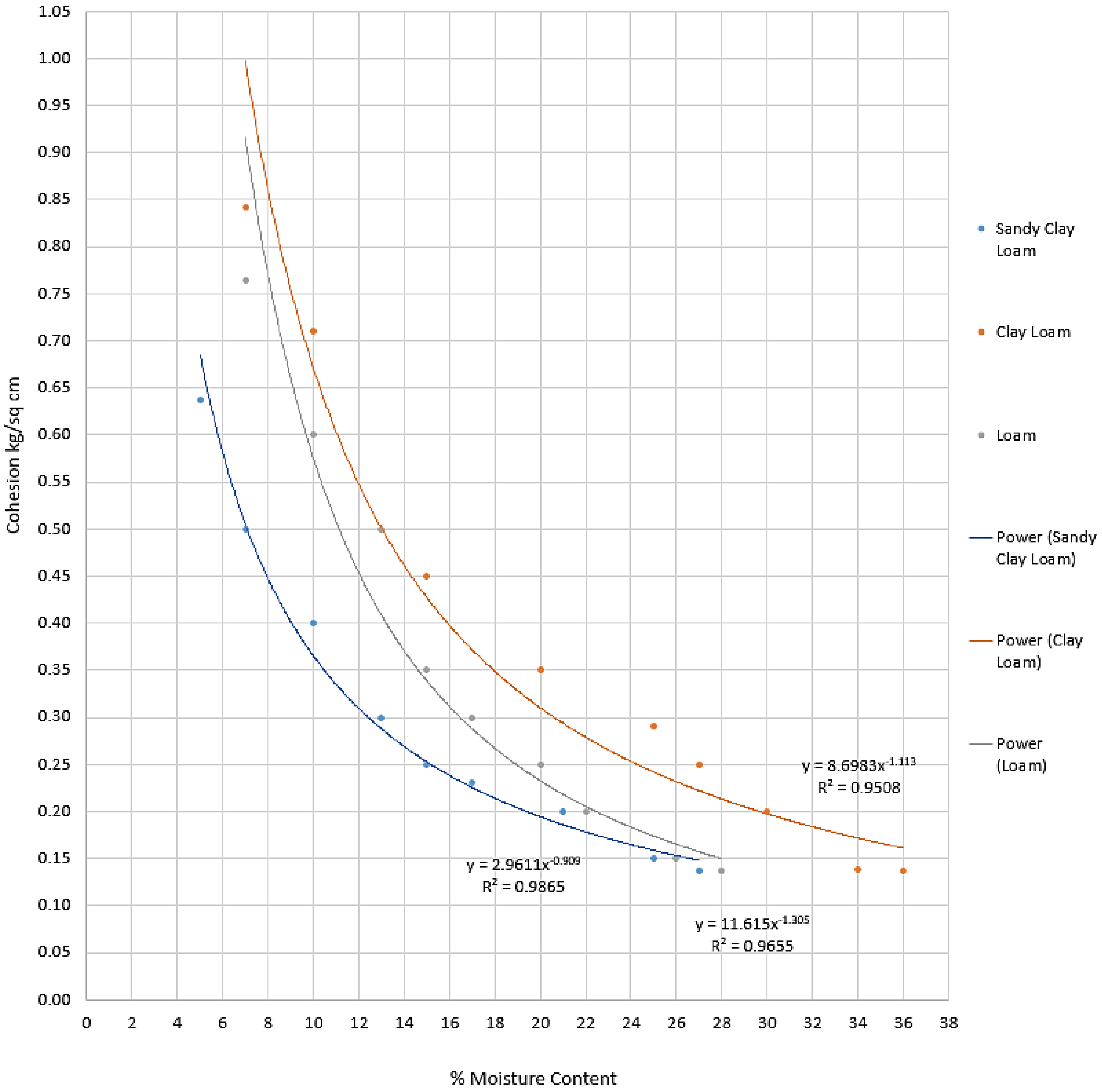

Figure 1. Relationship between cohesive strength and moisture content for the three soils.

HYDRUS-2D is a two-dimensional, finite element model provides a numerical solution of the Richards equation to simulate soil moisture and water flow in unsaturated soils. Richards equation can be denoted as:

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}+K(h)\right]-S(h) \tag{1}$$

Where *θ* denotes the soil volumetric water content [L^3 L^{-3}], *K(h)* is the unsaturated hydraulic conductivity [LT^{-1}], *x* and *z* the coordinates (horizontal and vertical) [L]. *S(h)* a sink term [L^3 L^{-3} T^{-1}] for the plant root water uptake, *h* signifies the soil water pressure head [L], and *t* is time [T].

To simulate a typical drip irrigation system, an emitter flow rate of q = 2.71 cm/hr was utilized in the model. For the simulations in this study, the emitterwas placed at 50 cm? below the soil surface in a domain area of 100 cm high by 200 cm wide. The model was then used to simulate a typical irrigation time of twelve hours. The initial condition assumed a soil-water content at field capacity (- 0.3 bars). The model results provided volumetric soil moisture content as a function of time and space in the solution domain described above. This wetting pattern was then utilized to determine horizontal spacing and appropriate depth placement of the tubing.

The increase in soil stress at any depth resulting from a surface load can be calculated using the Boussinesq equation:

$$\Delta \mathrm{p} = \frac{3\mathrm{P}}{\mathrm{Z}^2 * 2\pi * \left[1 + \left(\frac{\mathrm{r}}{\mathrm{z}}\right)^2\right]^{5/2}} \tag{2}$$

Where *P* is a point load at the surface (kg), Δp is the increase in stress (kg/cm^2) at a depth z below the surface and a radial distance r from the surface point load. This increase in stress is independent of soil properties. For uniform loads spread over a contact area, a set of tables developed by Newmark (Hough, 1969), can be used to determine the increase in stress under such uniform loads.

Results and Discussion

Extensive crops such as alfalfa which cover the surface require that field machinery periodically traverse the area. Such equipment produces a surface load spread over the contact areas of the wheels in contact with the surface. For this study, a four-wheel rubber-tired tractor was utilized with a rear tire that produced a footprint contact area of 86.36 cm x 42.92 cm = 3707.09 cm^2 (Brodbeck, 2004). The tractor weight was 3 300 kg dispersed 65% to the rear wheels and 35% to the front. The wheelbase was 2.33 m and wheel spacing 1.6 m. The greatest increase in stress would occur directly below one of the rear tires and would result from the load from that tire as well as the contribution to the stress increase from the other three tires. Since the effect of contact area decreases rapidly with depth, the Newmark solution of the Boussinesq equation for stress increase directly below one rear tire and the Boussinesq equation was utilized to calculate the contributions of the other three tires.

Once the soil wetting pattern from twelve hours of irrigation for each soil and the increase in stress at several depths due to a load of a tractor on the surface have determined,we were able to apply Mohr’s rupture theory to determine the depth and soil moisture conditions at which shear failure would occur due to the surface load.We could then use this information to determine the minimum depth placement to avoid this failure condition.

From Figures 2 to 7 it is show the modeled moisture content above the emitter the day of the cut after twelve hours of irrigation for the SCL, CL and L soils respectively. The moisture content reaches near saturation at 4 cm above the emitter for the SCL, 8 cm for the CL and 5 cm for the L soil. At those moisture contents, the soil has little or no shear strength, so the drip emitters will need to be placed at a shallower or greater depth to avoid failure due to the added load of the tractor. Table 2 shows increases in stress at depths up to 50 cm below the surface due to the load of the tractor on the surface.

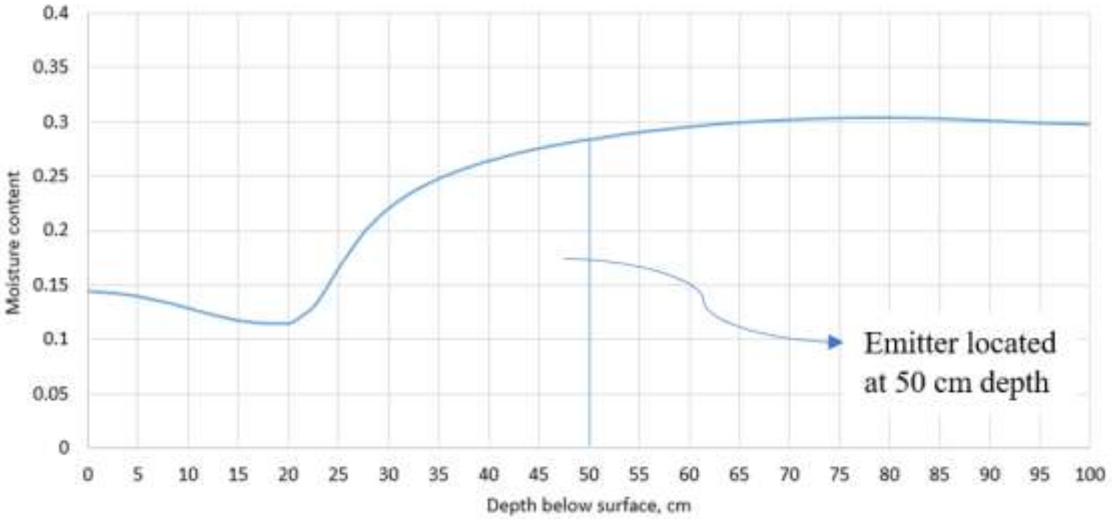

Figure 2. Moisture content (%) on the day of the cut, after 12 hours of irrigation, in SCL soil with a deph of placement of 50 cm.

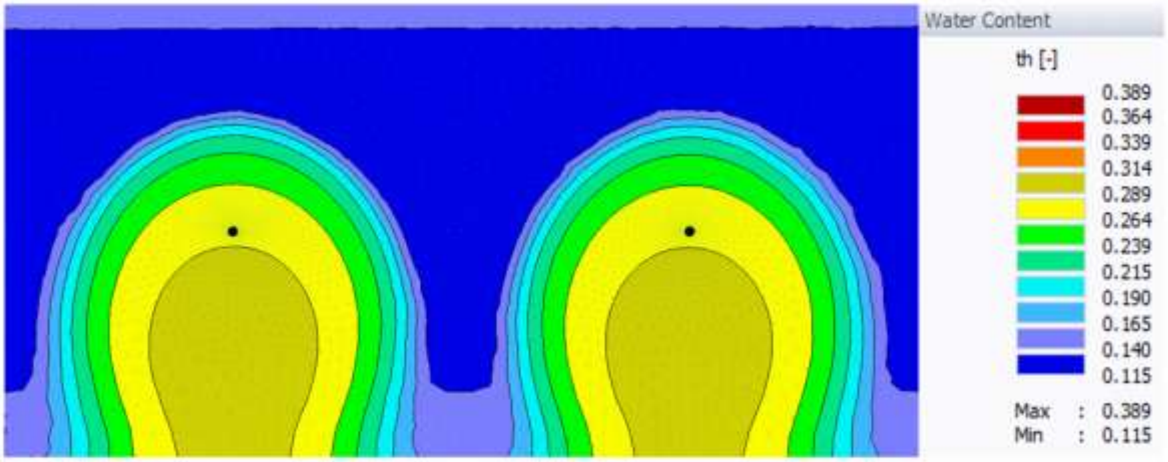

Figure 3. Graphical representation of the moisture content on the day of the cut, after 12 hours of irrigation, in the SCL soil with an emitter placement depth of 50 cm.

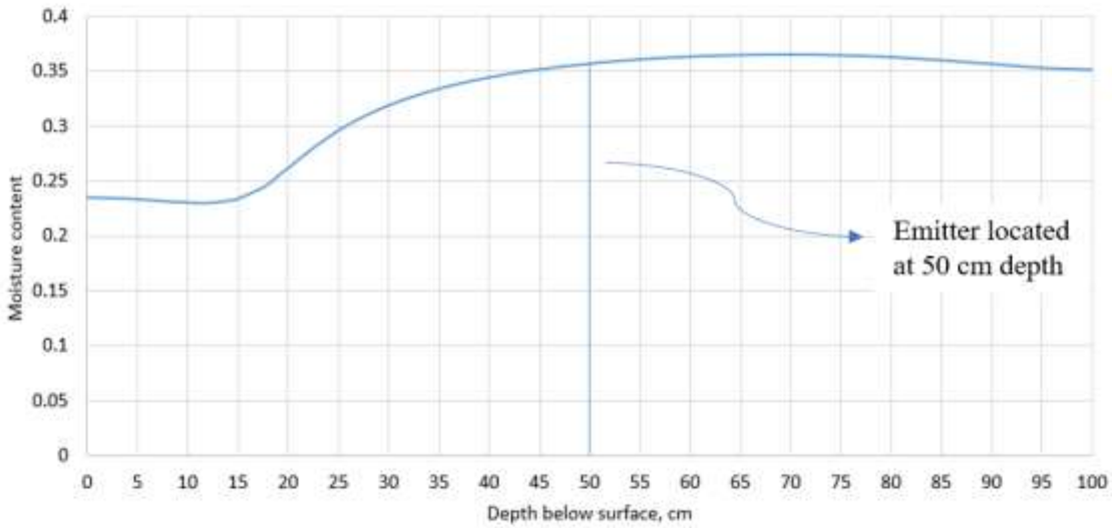

Figure 4. Moisture content (%), on the day of the cut, after 12 hours of irrigation, in CL soil with a deph of placement of 50 cm.

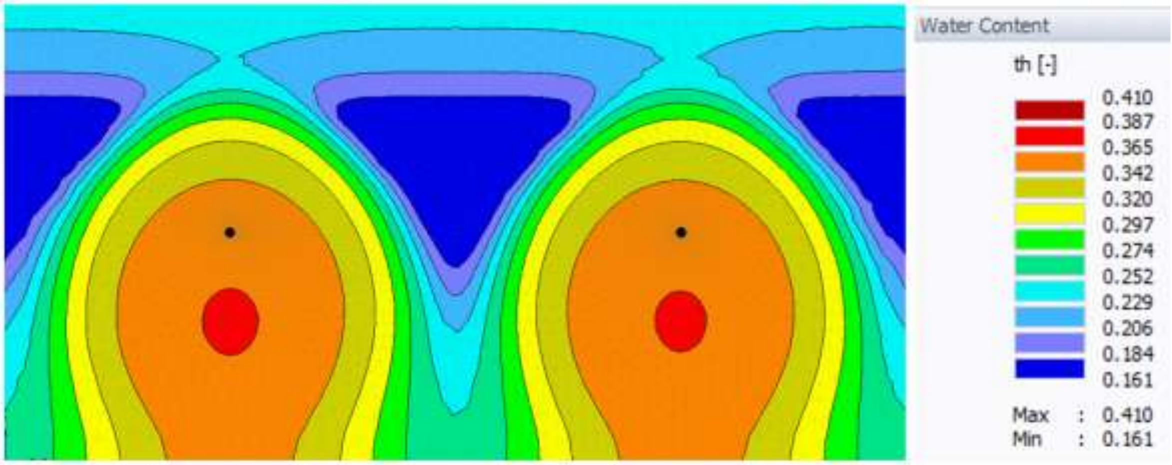

Figure 5. Graphical representation of the moisture content on the day of the cut, after 12 hours of irrigation, in the CL soil with an emitter placement depth of 50 cm.

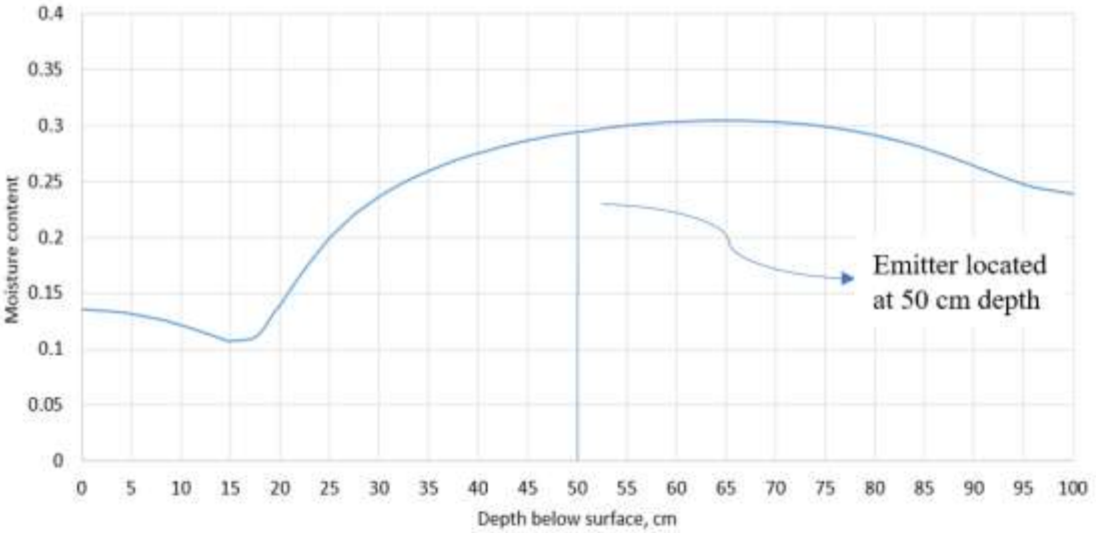

Figure 6. Moisture content (%) on the day of the cut, after 12 hours of irrigation, in L soil with a deph of placement of 50 cm.

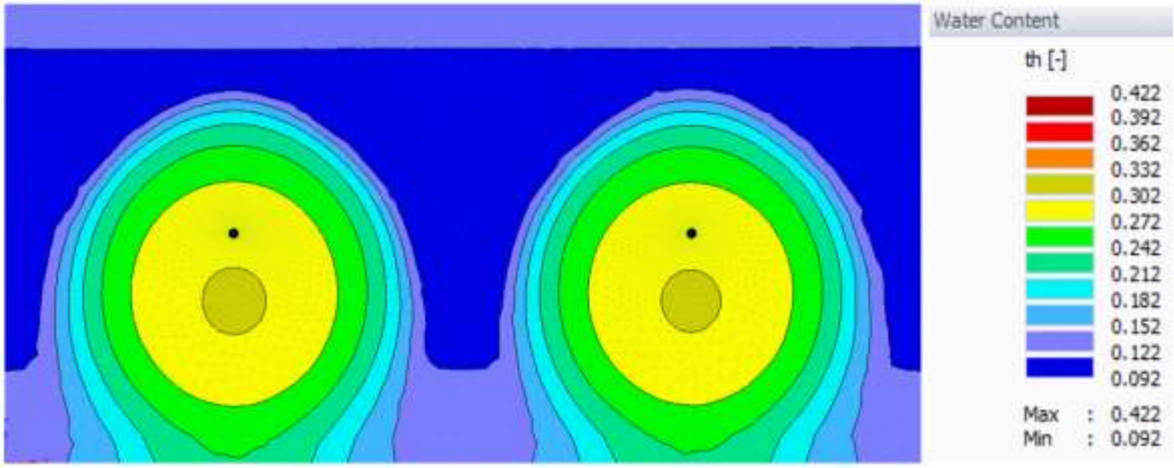

Figure 7. Graphical representation of the moisture content on the day of the cut, after 12 hours of irrigation, in the L soil with an emitter placement depth of 50 cm.

Table 2. Stress increase due to surface load of tractor

Depth of placement (cm)	Front tire #4 (kg/cm^2)
10	0.5902
20	0.4474
30	0.3204
40	0.1672
50	0.1189

Since the greatest increase in stress is near the surface, we used the stress increase at that depth to develop a Mohr's circle of failure and failure envelope for each soil using the stress increase at 10 cm depth. Figures 8, 9 and 10 show the results of this analysis for each soil.

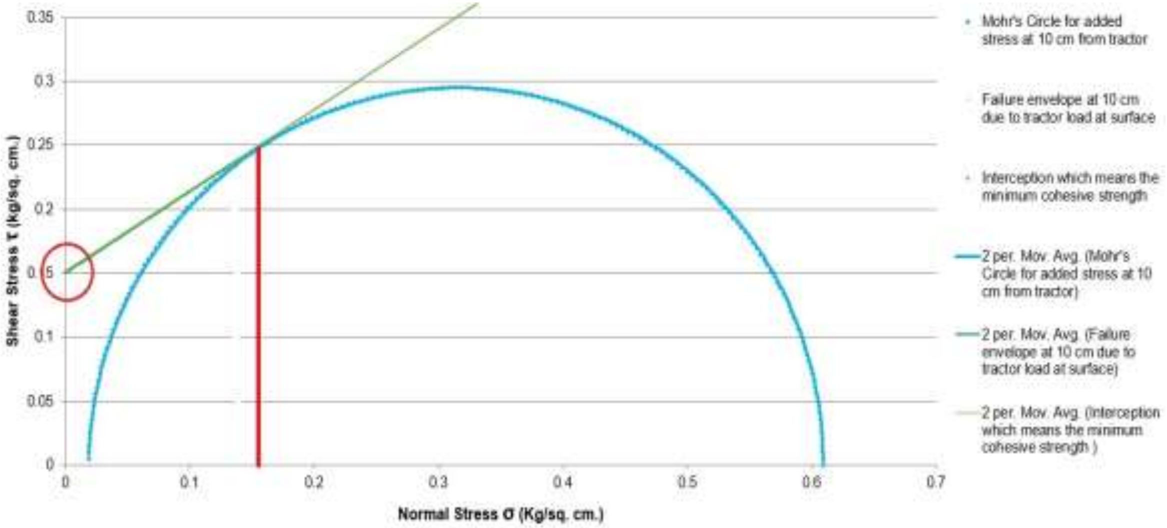

Figure 8. The minimum cohesive strength is of 0.15 kg/cm^2 in a Mohr's circle and failure envelope for SCL at 10 cm depth with a tractor load at the surface.

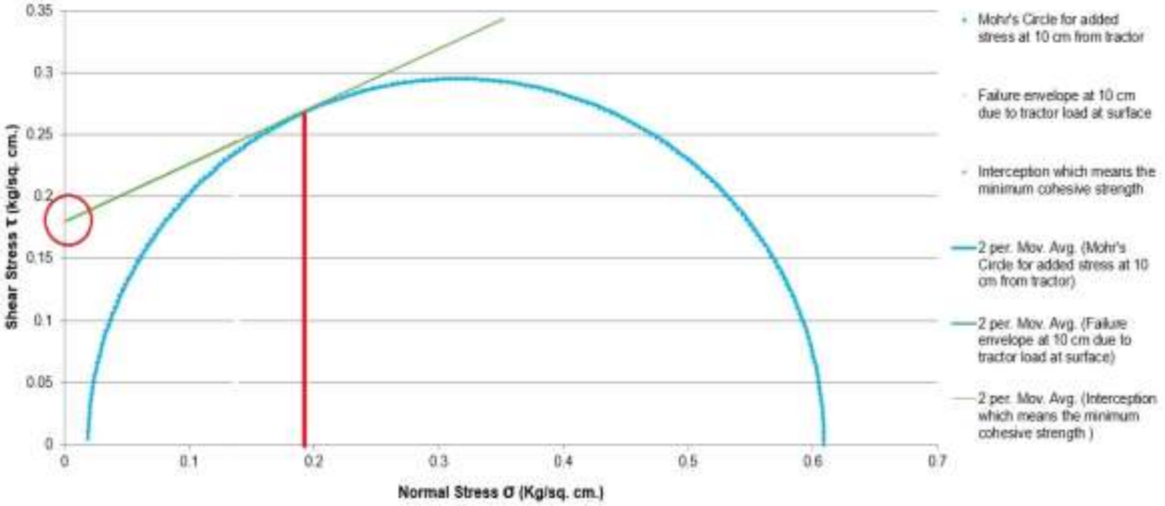

Figure 9. The minimum cohesive strength is of 0.18 kg/cm^2 in a Mohr's circle and failure envelope for CL at 10 cm depth with a tractor load at the surface.

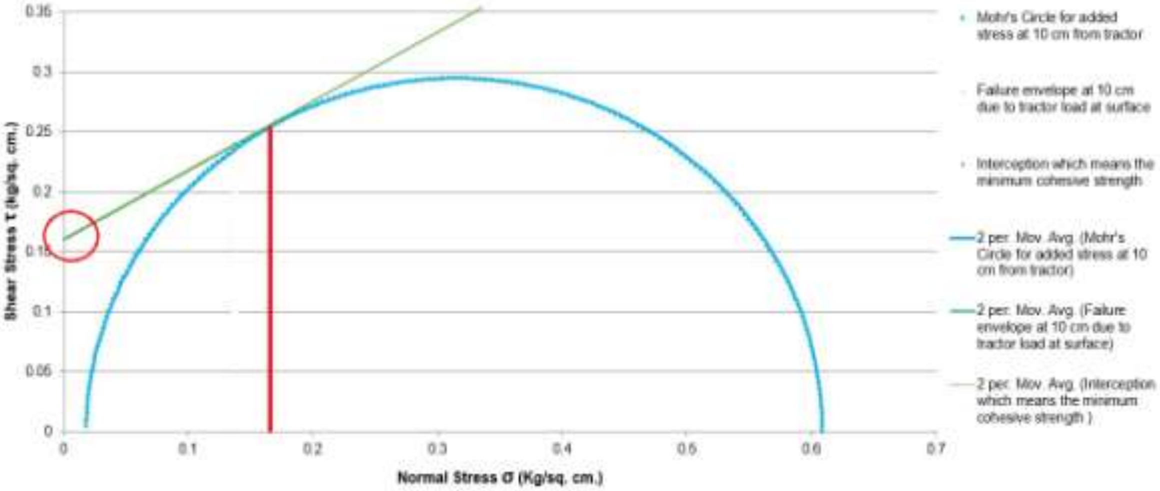

Figure 10. The minimum cohesive strength is of 0.16 kg/cm^2 in a Mohr's circle and failure envelope for L at 10 cm depth with a tractor load at the surface.

From Fig. 8, it can be seen that a minimum cohesive strength of 0.15 kg/cm^2 would be essential to avoid failure for the SCL soil. Similarly, from Fig. 9 and 10, it can be seen that the minimum cohesive strength for the Clay Loam and Loam would be 0.18 kg/cm^2 and 0.16 kg/cm^2 respectively. From Fig. 1 it can be seen that a cohesive strength of 0.15 kg/cm^2 occurs at a moisture content of about 26.8 % for the SCL which, from Fig. 2 it can be seen to occur at 10 cm above the emitter. Hence, the minimum placement depth for the SCL soil would be at 40 cm.

Correspondingly, it can be seen from Fig. 1 that the cohesive strength of 0.18 kg/cm^2 occurs at a moisture content of 32.7 % for the CL soil and from Fig. 4 it can be seen that this happens at 15 cm above the emitter giving us a minimum placement depth of 35 cm. For the L soil, similar analysis yields a minimum installation depth of 40 cm.

Finally, the greatest lateral extent of wetting after twelve hours of irrigation on the day of the cut is shown for each soil in Fig. 11. This represents one-half of the wetting pattern, so to attain adequate coverage, the horizontal spacing between emitters should be twice these values. Consequently, for the SCL spacing should be no more than 80 cm, for the CL no more than 90 cm, and for the L no more than 80 cm.

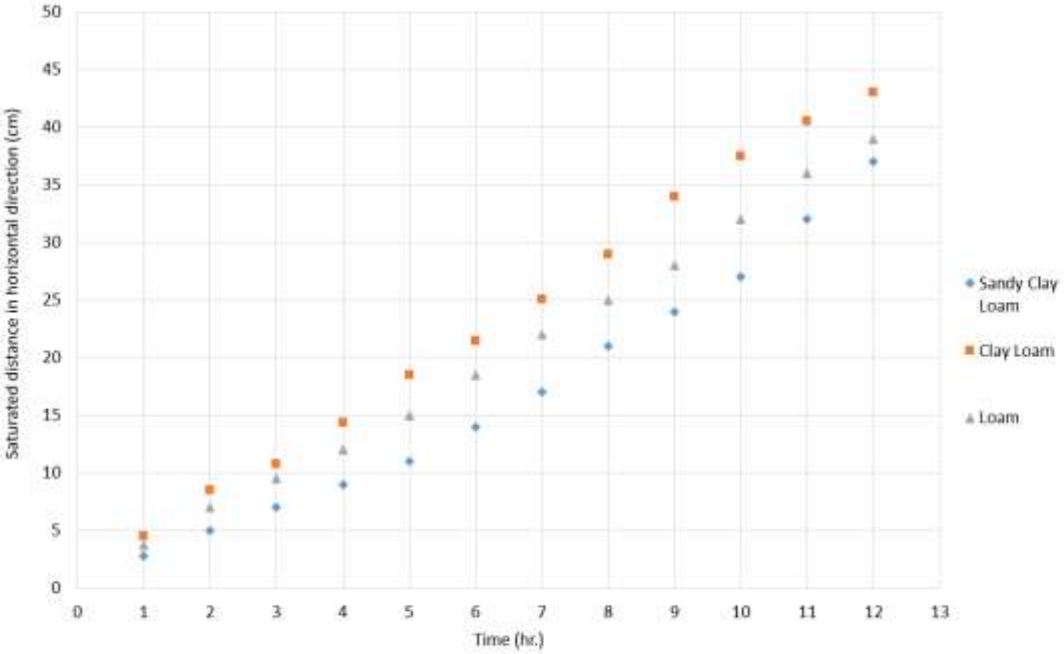

Figure 11. Horizontal extent of wetting for the three soils.

Conclusions

The analysis presented describes how the HYDRUS-2D model can be used in combination with soil shear strength and soil stress analysis methods to calculate a minimum depth of placement of drip irrigation tape to avoid soil failure due to added loads on the soil surface such the load added by a tractor during the harvesting process. This methodology was also used to determine maximum horizontal spacing using wetted patterns generated by the model.

Based on the analysis in this study, minimum depth placement for a drip emitter with a flow rate of 2.71 cm/hr would be 40 cm, 35 cm and 40 cm for the Sandy Clay Loam, Clay Loam and Loam soils respectivelyin order to avoid shear failure due to a tractor on the surface directly above the emitter with a weight of 3,300 kg. Maximum horizontal spacing for the soils was determined to be 80 cm for the Sandy Clay Loam, 90 cm for the Clay Loam, and 80 cm Loam soils. These values can be rounded to 1 m, and they are the adequate spacing in order to supply the adequate amount of water to the root-zone, increase production and avoid striping presence in the plots.

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